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RESEARCH ARTICLE

Experimental results of the tribology of aluminum measured with a pin-on-disk tribometer: Testing configuration and additive effects

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Abstract: The friction coefficient, wear rate, and wear coefficient of the aluminum metal surface were measured at room temperature (≈300 K) with a pin-on-disk machine at a fixed load of 196.2 N. Two different testing configurations were adopted: (1) aluminum pin vs. Helix oil-on-steel disk (AHS) and (2) aluminum pin vs. 10% Polytron plus 90% helix oil-on-steel disk (APS). In the AHS configuration, the wear of the aluminum surface was found to be approximately 70 μm; however, in the APS configuration the wear dropped to 20 μm, revealing a marked decrement of one-third of the wear of aluminum. The volume wear rate of the metal in the unaided Helix oil was estimated to be 1.28×10^{-3} mm^3/min. The additive minimized the volume wear rate of the aluminum metal by orders of magnitude to 6.08×10^{-5} mm^3/min. Similarly, the wear coefficient of the aluminum pin, calculated in the AHS configuration, rendered a value of 1.27×10^{-10} m^2/N. In the APS configuration, the same parameter was 4.22×10^{-11} m^2/N, that is to say, an order of magnitude lower than the preceding value. The observed coefficient of friction for aluminum is 0.012 in Helix oil and falls to a remarkably lower value of 0.004 through the Polytron additive. The experimental findings demonstrate that Polytron additive substantially lessens the wear of the aluminum surface; in effect, the wear coefficient and the wear rate decline linearly. This singularity may be linked to the ability of Polytron to impregnate the crystal structure of the metal due to its ionic character and the consequent adherence to the metallic surface as a hard surface layer.

Keywords: antiwear; Polytron additive; aluminum metal; lubrication; friction

1 Introduction

Beginning with the first mechanical device, lubrication has been an essential design parameter for any mobile parts involved in machinery, mechanical tools, and transport means. A variety of materials, in the forms of gas, liquid, or solid, were interposed between two surfaces in order to improve the smoothness of relative movement and to prevent damages to the surfaces. It was noticed that the variation of friction and wear rate depends on various interfacial conditions such as normal load, geometry, relative surface motion, sliding speed, surface roughness of the rubbing surfaces, type of material, system rigidity, temperature, relative humidity, lubrication, and vibration [1–13]. Nevertheless, for the alteration of friction and wear rate, sliding speed and normal load are considered to be of paramount importance. Similarly, it has been found that the friction force is a function of both velocity and time of contact and that the coefficient of friction may be very low for very smooth surfaces and/or at loads in the micro- to nano-newton range [14, 15]. Therefore, some authors have explored lubricants and have

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proposed them to be potential mediators for reducing friction and wear of the mating surfaces [16–18]. However, in applications like automobile engines and complex machinery, the base lubricant is not sufficient to give a long life to the sliding or mating parts. The usual solution is the addition of a relatively small amount of certain additive compounds that provide a significant improvement of the base oil properties with regard to either oxidative degradation or tribological and other performance characteristics [19–25]. Most of the additives comprise polar functional groups and belong to various classes of organic or organometallic compounds. In general, the triboactive additives contain active elements (or combinations thereof) such as phosphorous (P), sulphur (S), chlorine (Cl), zinc (Zn), nitrogen (N), tungsten (W), and carbon (C). A recent trend is the addition of nanoparticles to various lubricants. These components are capable of forming protective tribological inorganic or comparable layers on frictional surfaces due to reactions with the constituent material (typically iron and its alloys) [26–34]. The above-mentioned components and their nanocounter parts are often added up to 5 wt% as monomeric antiwear and extreme pressure agents for the prevention of serious metal surface depletion. In many applications the wear reduction mechanism and quantitative analysis of the additives are not well known and a thorough exploration is still inescapable. A literature survey reveals that research has been done on various materials and conflicting views have been advanced by different authors in favor of their results. However, research on an unusual and elusive additive known as Polytron is highly scarce; therefore, to the best of our knowledge the experimental work presented in this article seems to be the first of its kind. In this research study, this uncommon antiwear additive Polytron has been selected for an investigation to assess its wear reduction and friction minimization strategy. As such, the research dictates a scientific determination to understand the interaction mechanism of Polytron with metal substrates as well as the consequent smoothening and lubrication of the interacting surfaces. Polytron is an oily fluid mixture of petroleum-based chemicals mixed with oxidation inhibitors and detergent chemicals, which at ambient pressure and temperature is a stable grease in stark contrast to the conventional lubricants. Polytron additives, being petroleum based, contain no solid particles and are compatible with all the lubricants available in the market. Polytron comprises 80% para and 20% meta Polytron. The specialized Polytron metal treatment concentrate (MTC) is polarized, and it is attracted to metal surfaces and develops a durable polished-like microscopic layer through metallurgical process that can resist wear, extreme pressure, and excessive temperature. As such, this analysis was prompted to understand the effect of the Polytron additive on the friction and wear behavior of aluminum metal sliding against stainless steel. It can be suggested that Polytron is an effective antiwear additive in the Helix base oil and can intrinsically reduce friction and wear by orders of magnitude. Realistically, Polytron-lubricated systems can deliver consistent performance for longer than the anticipated duty cycle of the machinery and protect the system from wear and premature failures.

The aim of this research study is to bring out the second phase of our experimental outcomes regarding the Polytron additive in the Helix lubricant to clearly understand the impact of the reaction film of Polytron on the rubbing surfaces of the metals and the ensuing antiwear protection capability. Introductory effects with reference to the Polytron additive in the Helix lubricant can be found elsewhere [35, 36].

2 Materials and methods

2.1 Experimental apparatus

For recording the data of the wear tests, we used the pin-on-disk tribotester (TR–20LE) (Ducom Instruments, India). The apparatus was enclosed in a plexiglass box that could be purged with dry air or nitrogen. A hygrometer (ZEAL, England) was used to measure the relative humidity of the air in the chamber. A tachometer was used to measure the revolutions per minute of the rotating shaft. The force of friction was recorded as a function of time and measured by a piezoelectric transducer. A basic outline of the pin-on-disk device is given in Fig. 1. The device comprises a pin that can slide on a rotating horizontal surface (disk). The circular steel disk is fixed on a rotating plate (table) that has a long vertical shaft welded from the bottom surface of the rotating plate. The shaft

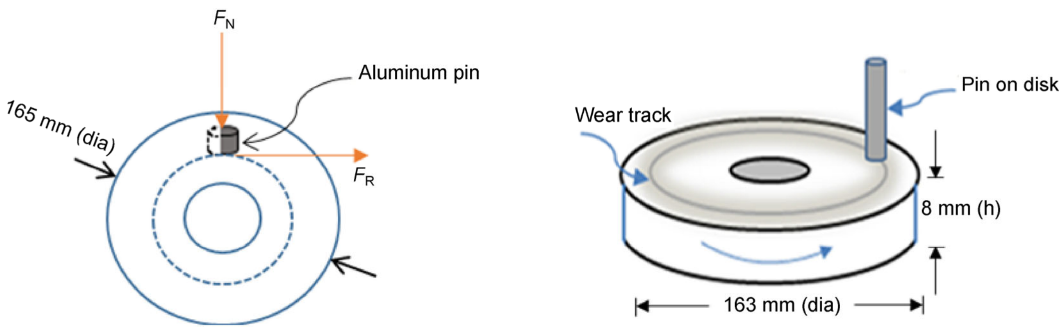

Fig. 1 Sketch of the pin-on-disk. The dimensions of the pin were 32 mm (length) by 10 mm (diameter); the dimensions of the disk were 165 mm (diameter) by 8 mm (height).

passes through three close-fitted bush-bearings that are rigidly fixed with three square plates in such a way that the shaft can move only axially and any that radial movement of the rotating shaft is restrained by the bush. In the sketch, F_N stands for the normal force (load) on the aluminum pin despite the fact that F_R represents the resistive force (friction) that arises from the sliding contact of the aluminum pin on the steel disk. Essential information vis-à-vis stainless steel disk and aluminum pin are enumerated in Tables 1 and 2. Moreover, the data sheets for the Helix oil and Polytron additive can be envisaged from Tables 3 and 4. One may discern from Table 4 that Polytron is

Table 1 Specification of the stainless steel disk (SUS304).

Property	Standard value
Disk dimensions	165 nm (dia) × 8 mm (h)
Counter bore	M5 holes from bottom × 4 nos
Counter bore	M5 holes from top × 4 nos
Holes	M4 tapped holes × 2 nos
Mechanical properties	
Density	8,000 (kg/m^3)
Young's modulus	190 (GPa)
Tensile strength	520 (GPa)
Yield strength	420 (GPa)
Poisson's ratio	0.27–0.30
Hardness (Brinell hardness)	88 (HB)
Chemical composition	
Carbon (C)	⩽ 0.08%
Silicon (Si)	⩽1.00%
Manganese (Mn)	⩽2%
Phosphorus (P)	⩽0.045%
Sulphur (S)	⩽0.30%
Nickel (Ni)	⩽8%–10.5%
Chromium (Cr)	⩽18.00%–20.00%

Table 2 Compositional analysis and mechanical properties of aluminum–silicon alloy pin (A390) [37].

Chemical composition	Minimum (by weight)	Maximum (by weight)
Silicon	0.4%	0.8%
Iron	No	0.7%
Copper	0.15%	0.15%
Manganese	No	0.15%
Magnesium	0.8%	1.2%
Chromium	0.04%	0.35%
Zinc	No	0.25%
Titanium	No	0.15%
Other elements no more than 0.05% each, 0.15% total		
Remainder aluminum 95.85%–98.56%		
Mechanical properties		
Hardness	112.65 VHN	
Density	2.72 g/cm^3	
Tensile strength	250.00	

Table 3 Typical physical characteristics of shell helix oil ultra (5W–40) taken from Ref. [38].

Properties	Method	Shell helix ultra
SAE viscosity grade		5W–40
Kinematic viscosity		
@40 ˚C cSt	IP 71	81.1
@100 ˚C cSt	IP 71	14.5
Viscosity index	IP 226	187
Density @15 ˚C (kg/L)	IP 365	0.856
Flash point PMCC (˚C)	IP 34	206
Pour point (˚C)	IP 15	–39
HTHS viscosity@150 ˚C (mPa·s)		3.68

Table 4 Data sheet of polytron taken from Ref. [39].

Physical/chemical property	Observation
State	Liquid
Color	Yellowish clear
Smell	Odourless
Specific gravity	60/60 ≈ 1.00
Boiling point range	>300 °C
Flash point	>200 °C
Viscosity @ 100 °F	SUS 391
Viscosity @ 210 °F	SUS 61
Water solubility (T = 20 °C)	Low
Evaporation point	Higher than ether

marketed in a liquid state and is yellowish as well as odorless in contrast to other solid additives. Its flash and boiling points are above 200 °C and 300 °C, respectively, and its solubility in water is very low. Basic information regarding the aluminum metal, steel disk, Helix oil, and Polytron were taken from Refs. [37–39].

2.2 Experimental technique

The experimental work was performed in the tribology laboratory of UKM at approximately 70% relative humidity and room temperature(≈300 K). The Helix base oil (Shell Helix ultra 5W–40) was supplied by the Shell Oil Company at Bandar Baru Bangi. The Polytron MTC was provided by the Malaysian association of productivity Petaling Jaya, Malaysia. Both samples were used as supplied. The solutions of the base oil Helix and the Polytron additive were prepared at ambient temperature and pressure. These solutions were then stored in brown bottles to eliminate possible light-induced degeneration. Graduated cylinders were used for the precise addition of the base lubricant and the additive. The glassware and containers used in the experiment were thoroughly rinsed with ethanol and dried in an oven for 2 h at 110 °C. For the tribotester, we used a soft aluminum–silicon alloy (A390) as pin and stainless steel (SUS304) as the disk material. The pure aluminum pins (less than 0.1% impurities) were given a final polish with 10 μm alumina and then annealed in a vacuum furnace above the recrystallization temperature and cooled slowly in order to give a uniform hardness for all of the pins so as to acquire reproducible wear measurements. The disk was lap ground and given a final polish of 60 μm SiC. The data was obtained for separate test runs with the Helix base oil and then with Polytron (10%) as an additive. Wear rates were calculated from the measured weight loss of a pin after rubbing for a definite time (i.e., 240 min). The mass and volume of the pin were measured both before and after running the experiment. The mechanical properties of the pin before and after running the machine are presented in Tables 5 and 6. The wear experiment was performed by sliding the aluminum pin having a hemispherical tip (diameter: 10 mm) on the hardened steel disk. A fixed load of 20 kg was applied on the pin by a pulley system. For each run of the experiment, an unworn position of the pin and a different face of the disk was used. For the pin-on-disk experiment, we took 2,000 mL of Helix oil in a graduated cylinder. In the first instance, 100% Helix base oil was used and its volume was 2,000 mL. In the second instance, 1,800 mL (90%) base oil was mixed with 200 mL (10%) Polytron. The lubricant was applied to the disk surface at a constant flow rate of almost 0.5 mL/min and the disk was completely covered with lubricant before running the test. The wear volume was calculated from the pin wear scar diameters. Typical wear versus time curves were obtained with Matlab software and polynomial fitted to discern the trend

Table 5 Specifics of the aluminum pin and stainless steel disk and experimental results of the wear test in the Shell Helix oil (5W–40).

Test parameter	Specific/computed value
Wear of aluminium pin	70 ± 0.1 micron
Before the wear run	
Material of the wear disk	Stainless steel 304
Diameter of the wear disk	80 mm
Mass of the pin	6.4480 g
Length of the pin	32.00 mm
During the wear run	
Speed of the wear disk	500 rpm
Time allocated	14,400 s ≈ 240 min ≈ 4.0 h
Sliding speed	2.09 m/s
Sliding distance	30,163.2 m ≈ 30.163 km
After the wear run	
Mass of the pin	6.4470 g
Length of the pin	31.981 mm

Table 6 Experimental particulars of the wear tests of aluminum pin in the Shell Helix oil (5W–40) mixed with 10% Polytron additive.

Test parameter	Specific/computed value
Wear of aluminium pin	20±0.1 micron
Before the wear run	
Quantity (Helix Oil)	2,000 mL
Load	196.2 N
Material of the pin	Aluminum–silicon alloy (A390)
Mass of the pin	6.4480 g
Pin diameter	10.00 mm
Length of the pin	32.00 mm
Material of the wear disk	Stainless steel SUS 304
Diameter of the wear disk	80 mm
During the wear run	
Speed of the Wear Disk	500 rpm
Time allocated	14,400 s ≈ 240 min ≈ 4.0 h
Sliding Speed	2.09 m/s
Sliding Distance	30,163.2 m ≈ 30.163 km
After the wear run	
Mass of the pin	6.4472 g
Length of the pin	31.996 mm

of the data points. This practice was reiterated for each solution and each condition in an independent test. A series of experiments were performed successively and the same data set was obtained from each experiment. As such, the experimental error was negligibly small in the data. To identify the extraordinary contribution of the Polytron additive in the Helix lubricant, three key tribological parameters, viz., mass wear rate, volume wear rate, and wear coefficient were calculated. They are defined by Eqs. (1), (2), and (3), respectively. The quantitative values of these parameters are listed in Table 7.

$$\text{Mass wear rate} = m/t \ (\text{mg/min}) \tag{1}$$

$$\text{Volume wear rate} = V/t \ (\text{mm}^3/\text{min}) \tag{2}$$

$$\text{Wear coefficient } (k) = (V\times H)/(N\times S) \tag{3}$$

3 Results and discussion

The experimental results and polynomial-fitted curves of the wear behavior of the aluminum metallic pin in the AHS and APS configurations are portrayed in Figs. 2 and 3. The wear curves have been plotted with respect to time and sliding distance as well. Moreover, it is evident from these curves that Polytron provides an outstanding wear relief in the system comprising the aluminum pin on a steel disk. From the graphs, it can be anticipated that the wear in the AHS configuration is approximately 70 μm, whereas in the APS configuration the wear stands nearly at 20 μm. Then, for the same two configurations, the progress of the coefficient of friction with reference to time as well as sliding distance has been plotted and is shown in Figs. 4 and 5. The experimental conditions for the adopted configurations were all the same. One can easily notice that in the AHS conformation the introductory value of the friction coefficient is almost zero and increases almost linearly to a value of 0.012 in a time span of 100 min of rubbing. After that, it remains almost constant for the remaining of the experimental time. On the other hand, in the APS arrangement, the coefficient of friction starts from a value of 0.005 and then declines to a value of 0.004. It is recognizable that Polytron reduces the wear of the pin in a significant way which, in effect, is more than a factor of three. It is found that our findings are significantly better than the research findings of other researchers done on various additives. With Polytron additive, we may predict that wear and friction reductions are admirably more pronounced than that found by Chowdhury and Khalil [40]. In addition, our findings are far better than the results shown by Miroslav and Slobodan [41], Riyadh et al. [42], and

Table 7 Computed tribological parameters of the aluminum pin. The error limit is ± 0.1.

Parameter	Helix (100%)	Helix (90%) + Polytron (10%)
Wear	70 μm	20 μm
Mass-wear rate	3.33×10^{-3} mg/min	8.33×10^{-4} mg/min
Volume-wear rate	1.28×10^{-3} mm^3/min	6.08×10^{-5} mm^3/min
Coefficient of friction	0.012	0.004
Wear coefficient (k)		4.22×10^{-11} m^2/N
Total mass loss	0.7992 mg (in 240 min)	0.1992 mg (in 240 min)
Total volume loss	0.3079 mm^3 (in 240 min)	0.01459 mm^3 (in 240 min)

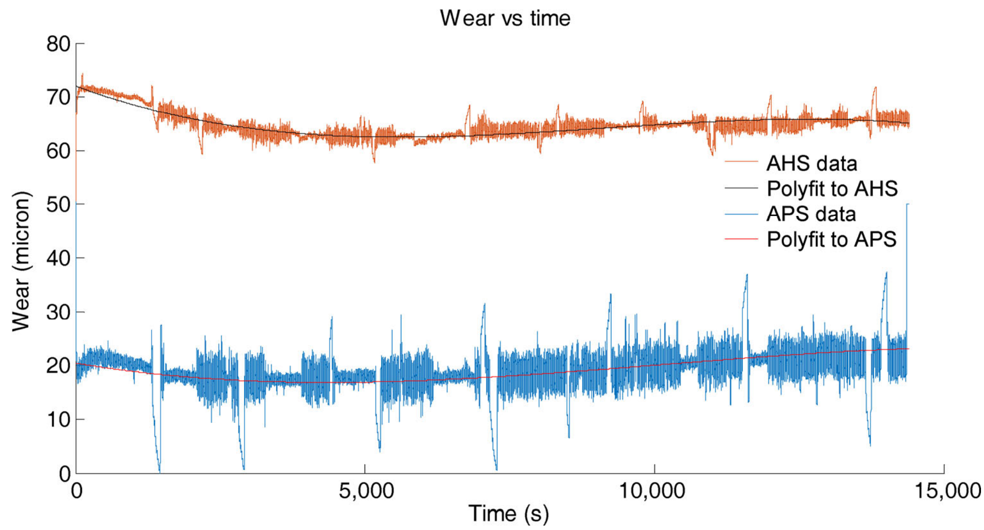

Fig. 2 Comparison plot of the wear of aluminum against time for the base oil helix and the additive (polytron); the apportioned time for both the experiments was 240 min. Graph illustrates both the actual variation and polynomial-fitted trend of the data points.

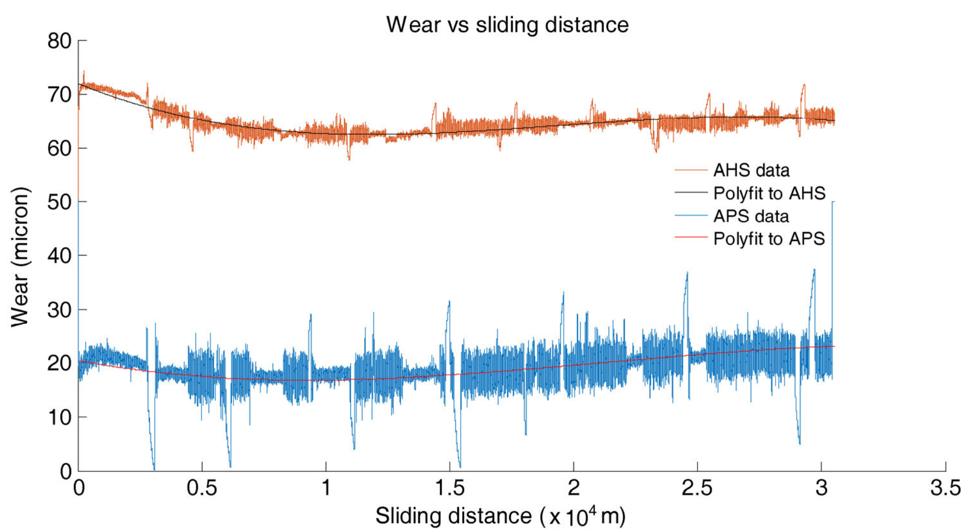

Fig. 3 Comparison plot of the wear of aluminum against sliding distance for the base oil helix and the additive (polytron); the sliding distance for both the experiments was fixed at 30.163 km. Graph illustrates both the actual variation and polynomial-fitted trend of the data points.

Bhushan and Kulkarni [43] in their experimental judgments. The mass and volume losses of the aluminum pin were also probed in both the configurations. The comparison curves for the mass losses are shown in Figs. 6 and 7, whereas the comparison curves for the volume losses are depicted in Figs. 8 and 9. To elucidate the influence of the additive, the graphs were drawn both with respect to time and sliding distance as well. The contrast is very clear and prominent in the two types of configurations. Without additive, the two types of losses are considerably larger and increase in direct proportion with the passage of time and/or with the coverage of sliding distance. Contrariwise, the additive reduces both losses by orders of magnitude; reasonably, the losses are significantly small in the presence of the Polytron additive. This suggests a strong interaction of the lubricating medium with the steel surface in the presence of Polytron which, in turn, points to a conspicuous reduction in the wear scar of the aluminum

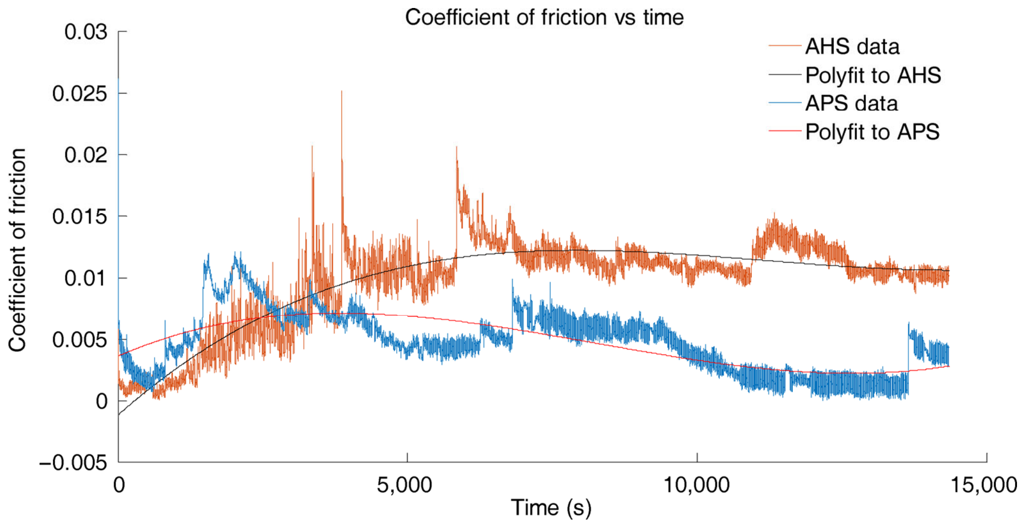

Fig. 4 Comparison plot of the coefficient of friction of aluminum against time for the base oil helix and the additive (polytron); the allocated time for both the experiments was fixed at 240 min. Graph illustrates both the actual variation and polynomial-fitted trend of the data points.

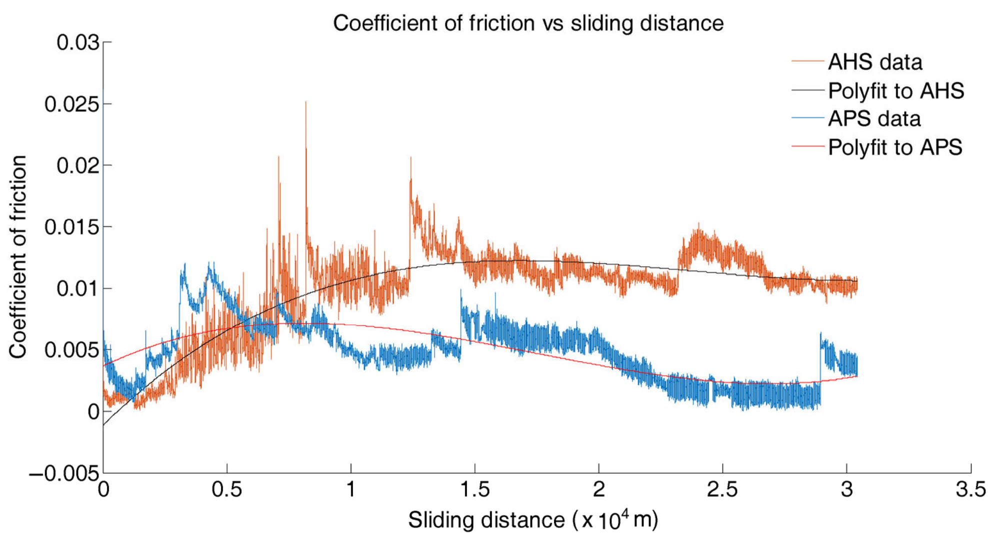

Fig. 5 Comparison plot of the coefficient of friction against sliding distance for the base oil helix and the additive (polytron); the sliding distance for both the experiments was fixed at 30.161 km. Graph illustrates both the actual variation and polynomial-fitted trend of the data points.

metal and the prospective use of Polytron as an antiwear additive. Friction is extensively reduced and wear is significantly curtailed that shall maximize the equipment life and performance and, in turn, will aid the oil and fuel economy. This observation with the Polytron additive is quite contrary to the high wear rate results of other researchers like Suarez et al. [44] who studied the popular ZDDP additive in mineral oil stock and Ghose et al. [45] who studied TCP and found considerably higher wear rates in their findings. By the same token, our research revelations in the APS configuration have produced better improved values for the friction coefficient, wear, and other tribological parameters than the conclusions of Anand et al. [46] who used phosphonium ionic liquid additives in diesel engine lubricants. Besides, our experimental judgments on wear and friction waning with Polytron additive are even far superior to the findings of Chen et al. [47] and Abdullah [48, 49] for nanoadditives in different lubricating media. This suggests that Polytron is

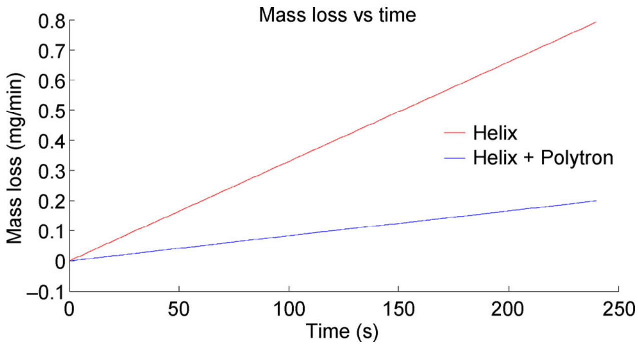

Fig. 6 Comparison plot of the mass loss against time for the base oil helix and the additive (polytron); the allocated time for both the experiments was fixed at 240 min. Graph illustrates the actual variation of the data points.

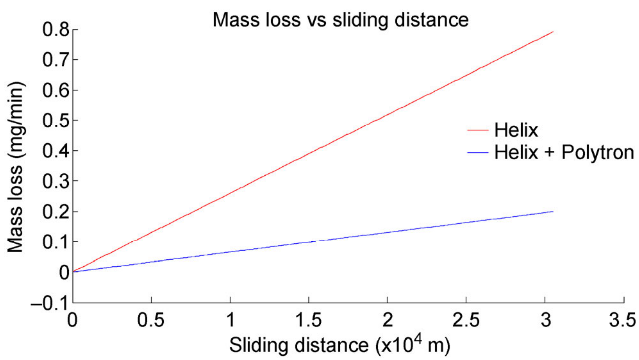

Fig. 7 Comparison plot of the mass loss against sliding distance for the base oil helix and the additive (polytron); the sliding distance for both the experiments was fixed at 30.161 km. Graph illustrates the actual variation of the data points.

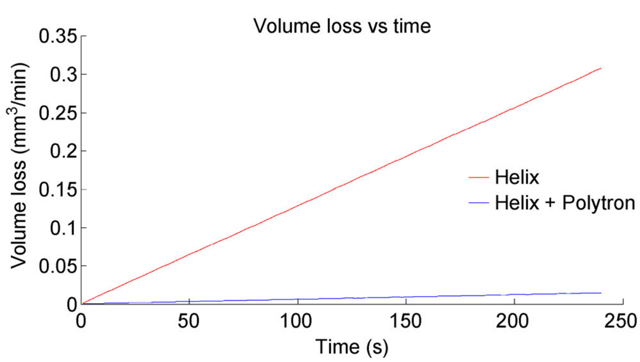

Fig. 8 Comparison plot of the volume loss against time for the base oil helix and the additive (polytron); the allocated time for both the experiments was fixed at 240 min. Graph illustrates the actual variation of the data points.

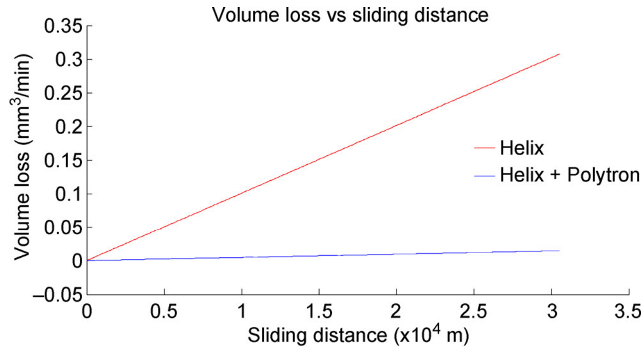

Fig. 9 Comparison plot of the volume loss against sliding distance for the base oil helix and the additive (polytron); the sliding distance for both the experiments was fixed at 30.161 km. Graph illustrates the actual variation of the data points.

protecting the surfaces, probably by forming a hardly adsorbed layer on the surfaces due to its ionic nature. It is expected that Polytron will adsorb on polar steel surfaces due to its own polar character, thereby protecting the surfaces against wear, and it is this protective layer that finally breaks down the resistive force of friction between the contacting surfaces. Finally, it can be easily concluded from the calculations presented in Table 7 that Polytron declines the rate of both mass as well as volume losses of the aluminum pin by an order of magnitude. The data altogether exposes the fact that the Polytron additive substantially cuts the wear of the aluminum surface and minimizes the friction between the contacting surfaces which may be related to its ability to impregnate the surface of the aluminum metal crystal structure and the consequent adherence to the metallic surface as an unbreakable surface film.

4 Conclusions

The wear of the aluminum metal surface in the AHS configuration was found to be circa 70 μm. Nevertheless, working with 10% by volume of Polytron additive in the APS configuration, all the same, the value of wear declined to 20 μm characteristic of more than two-third decrement in the wear. Likewise, the mass wear rate of the metal in the AHS mode was estimated at 3.3×10^{-3} mg/min which decreased by an order of magnitude in the APS mode to a value of 8.33×10^{-4} mg/min. The curves for the coefficient of friction in the AHS mode exhibited a value of 0.012 for the friction coefficient which diminished to a remarkably low value of 0.004 in the APS mode. It can be asserted that Polytron is an effective antiwear additive in the Helix base oil and can intrinsically reduce friction and wear by orders of magnitude.

Acknowledgments

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Nomenclature

m	Worn out mass of the aluminum pin in mg
t	Time span of the experiment in minutes
V	Worn out volume of the aluminum pin in mm^3
H	Hardness of the sliding pin
N	Normal load
S	Sliding distance in m
AHS	Configuration of the aluminum pin vs. helix-on-steel disk
APS	Configuration of the aluminum pin vs. 10% polytron plus 90% helix-on-steel disk
AW	Antiwear
EP	Extreme pressure
MTC	Metal treatment concentrate
F_N	Normal force (load)
F_R	Resistive force (friction)
TCP	Tricresyl-phosphate
ZDDP	Zinc dialkyl-diethylthiophosphate

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